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13. ABSTRACT

A 120-degree beamwidth sonar transducer with the sensor elements in the array sparsely spaced is described. The radiational characteristics of the transducer array were investigated through the application of a computer program, and from the investigation it was determined that a sensor packing factor of 52 percent was permissible in the design. The fabrication and assembly of the transducer is described, and evaluation test results reported. An improved transducer array with wide-angle transmission characteristics has been developed for sonar purposes.

Details of illustrations in this document may be better studied on microfiche

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INTRODUCTION

BACKGROUND

For many years the United States Navy has been interested in the development of underwater electroacoustic transducers for utilization in various types of sound detection equipment. The Navy has been particularly interested in the development of transducer arrays that will produce acoustically a broad beamwidth in one plane and a narrow beamwidth normal to this plane of orientation. One technique for broadening the transducer beamwidth is through the use of a wedge-horn as reported in Reference 1. From this experimental investigation it was shown that wedge-shaped acoustic horns have moderate directivity with minor lobes at least 40 db below axial response. A more recent technique investigated at Naval Coastal Systems Laboratory (NCSL) involved the conformal shaping of diced piezoelectric ceramic elements to the radius of curvature of a right circular cylinder or to the section of a sphere. Although each of these techniques have shown various degrees of success for sonar applications, there has also been a need for reducing the bulk, complexity, and costs for these transducer arrays. This report will describe a new design method for simplifying the mechanical structure for the transducer array and still retain broad radiational characteristics.

TRANSDUCER APPLICATION

The transducer array described in this report was developed for use in a special low cost sonar system. In general, it was required that the array be operated at 100 kHz with beamwidths of 120 and 10 degrees in mutually perpendicular planes, and fabricated in a simple and expeditious manner to minimize costs.

SUMMARY OF DESIGN EFFORT

A computer program was used to analyze the radiational characteristics of several curved-faced transducer designs. This program allows the designer to arbitrarily change important design parameters such as radius-of-curvature, spacing of the sensor elements, and the number of elements contained in an array. Numerical results show that the sensor

elements can be widely spaced, and that an array factor of 52 percent is feasible.

A full size transducer array employing sparsely-spaced sensor elements will be described, and the method used for mounting the sensor elements and conformally shaping the array will be discussed. Also, analytical and experimental results will be compared.

ANALYTICAL APPROACH TO DESIGN

ARRAY GEOMETRY

The beamwidth requirements for the transducer array described in the introduction suggests that the transducer array be configured to the radius of a right circular cylinder. With the selection of a radius-of-curvature, the arc length of the array can be calculated. Likewise, the vertical height of the array can be determined for a given beamwidth and frequency of operation. The basic geometry of the array is illustrated in Figure 1 with reference to a XYZ axis of orientation. In this report, the array directivity will be referenced to either the XY-plane or YZ-plane.

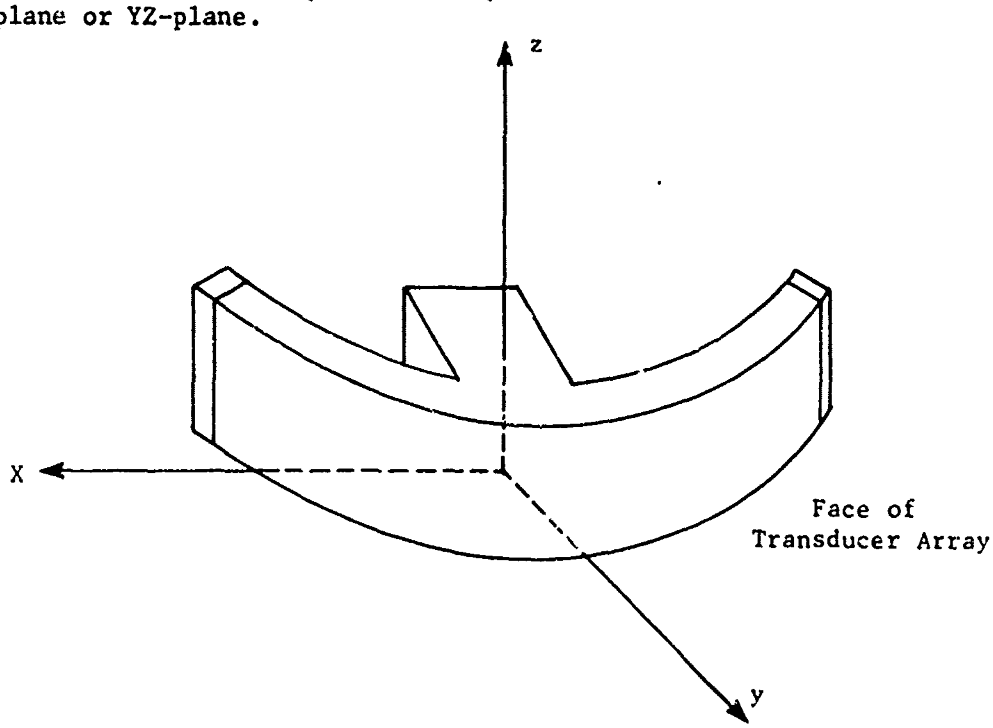

FIGURE 1. ARRAY GEOMETRY WITH RESPECT TO A XYZ AXIS

At this point the designer is confronted with the decision of selecting an appropriate radius-of-curvature for the array and how many sensor elements will be required. The selection of these parameters must be made while considering the physical effects of temperature rise and cavitation. Physical data describing cavitational phenomena and the properties of piezoelectric ceramic materials can be found in the literature; however, specific information related to electroacoustic transducer arrays has not been well documented. Thus, the designer will probably consider previous designs before finally selecting a radius-of-curvature for the array.

The vertical height of the array will be constant regardless of the radius-of-curvature selected.

COMPUTATION OF ARRAY DIRECTIVITY IN XY-PLANE

NSRDL computer program 1520V, *The Relative Directivity Pattern of a Curved-Face Transducer in the Plane of Transducer Curvature,* was used to investigate the radiational characteristics of several transducer designs. The 1520V program was modified from an Applied Research Laboratory program written sometime during 1966 for operation on a CDC 3200 computer. Basically, program 1520V is based on an equation found in the appendix of Reference 2. That is:

$$p(P) = C\sum_{m=1}^{m}\left[1 + \cos(\theta - \alpha_m)\right] \cdot e^{-ika\cos(\theta - \alpha_m)} \cdot p(\alpha_m)$$

$p(P)$ = pressure at some point remote to the transducer face

m = number of degrees over which pattern is desired

θ = the angle of calculation and varies from 0° to m°

α_m begins at NE-1/2 radians and is incremented by $\Delta\alpha$ to approximate the original arc in radians

β is dependent on α and θ incremental change differences.

where

C = constant

$p(\alpha_m) = e^{ika\cos(\theta - \alpha_m)}$

and

$$k = \frac{2\pi f}{c} = \frac{2\pi}{\lambda}$$

where

f = frequency

c = velocity.

Figure 2 shows the placement of α, β, and θ with θ varying from 0 to m degrees. In program 1520V, the designer may select the following design parameters:

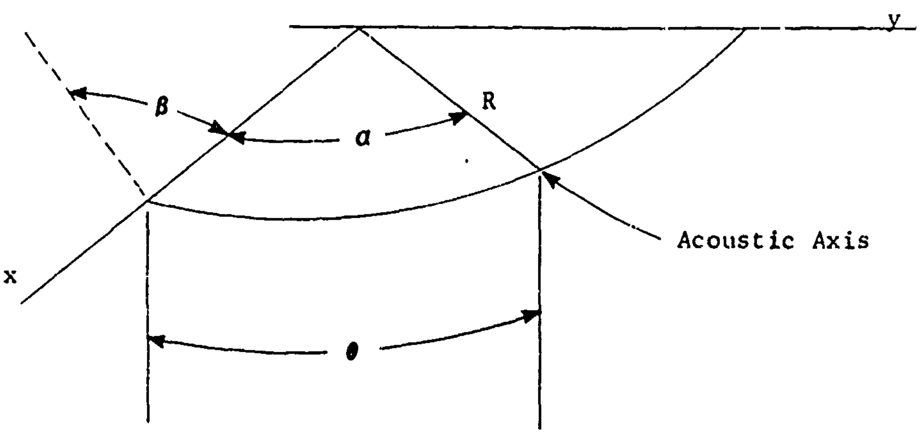

FIGURE 2. COORDINATE SYSTEM FOR CALCULATING DIRECTIVITY

1. arc length

2. center-to-center spacing of sensor elements

3. number of sensor elements in the array (NE)

4. amplitude shading.

Figure 3 shows the relationship between element spacing and center-to-center spacing.

In Figure 4 the analytical results of keeping the "D" and "S" parameters constant while increasing the radius-of-curvature and number of elements for the array are shown. From these results it appears that

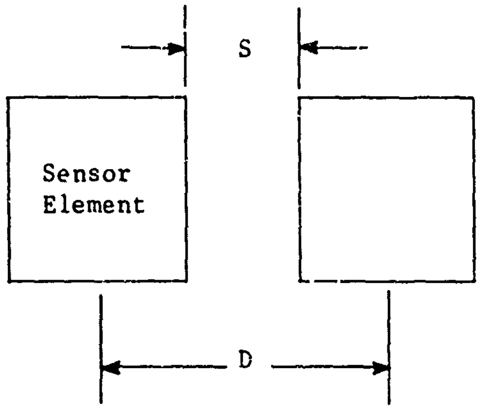

FIGURE 3. ELEMENT SPACING

there is no significant difference in the directivity pattern due to changes in radius-of-curvature over the range investigated. Conversely, the radius-of-curvature was held constant while element spacing and number of elements were varied. The results of the latter calculations are presented in Figure 5. Here one can readily see the futility of attempting to use too few elements spaced too far apart. Part of the data contained in Figure 5 will also be compared to experimental data in a later section of the report.

Based on the preceding efforts and the desirability of maintaining mechanical symmetry with a liquid-filled acoustic lens, the following design parameters were chosen for the array design:

1. Radius-of-curvature 9.5 inches

2. Center-to-center spacing of elements 0.374 inch

3. Element width 0.172 inch

4. Element thickness 0.335 inch

5. Width between elements 0.202 inch

6. Total number of elements in array 62.

Therefore, in terms of wavelength the center-to-center spacing of the elements is 0.624λ, and element width is 0.286λ. These are acceptable transducer design parameters.

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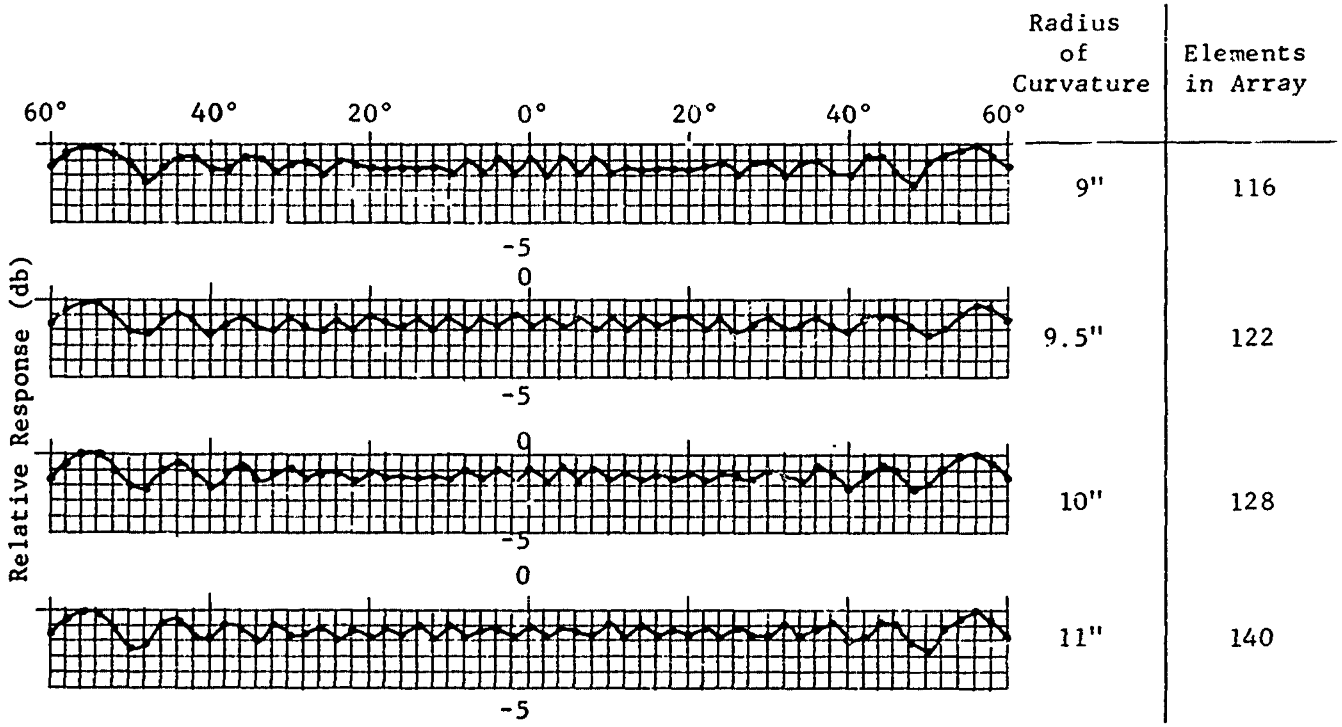

FIGURE 4. DIRECTIVITY IN XY-PLANE, THEORETICAL CALCULATIONS

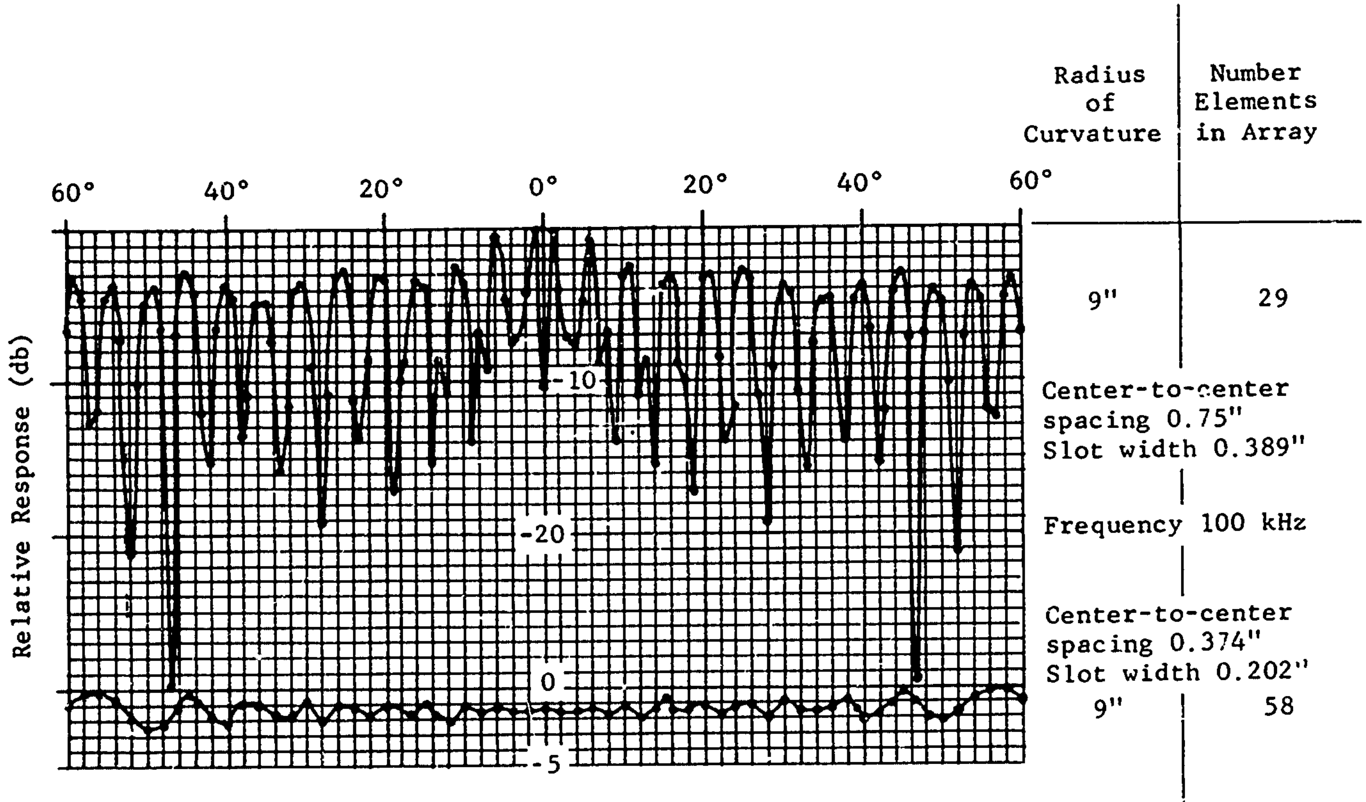

FIGURE 5. DIRECTIVITY IN XY-PLANE, THEORETICAL CALCULATIONS, WIDE-SPACED ELEMENTS

COMPUTATION OF ARRAY DIRECTIVITY IN YZ-PLANE

The directivity of the array in YZ-plane can be calculated by the directivity function of a straight line source as given in Table 3.1 of Reference 3. The function is stated as sin X/X

where

$X = \pi \ell / \lambda \sin \theta$

λ = wavelength in water

ℓ = length of the line source

θ = angle referenced to acoustic axis.

The theory and use of the above expression is found in Reference 4, and further discussion in this report is not warranted.

Based on the requirement for a 10-degree beamwidth at the -3 db down points in the YZ-plane, the vertical height of the array was calculated to be 3.1 inches. Acoustic tests were performed on a single sensor element to verify the radiation characteristics of the array in the YZ-plane of orientation.

GENERAL DESCRIPTION OF TRANSDUCER ARRAY

GENERAL

The general appearance of the transducer array is illustrated in Figure 6. Major components in the transducer system have been identified except the piezoelectric elements located inside the transducer housing.

TRANSDUCER HOUSING

The structural details of the transducer housing are contained in NSRDL Drawing Number 13275 titled *"Sonar Projector Housing No. LZP-MH-No 8."* The housing was basically fabricated from 5086 aluminum and the assembly anodized for corrosion retardation purposes. In Figure 7 the housing is shown without fixtures or attachments. Present experience indicates that the transducer housing can be fabricated in 2 to 3 man-days. An alternate approach in construction would be to make an aluminum casting, and no doubt a significant cost reduction could be achieved.

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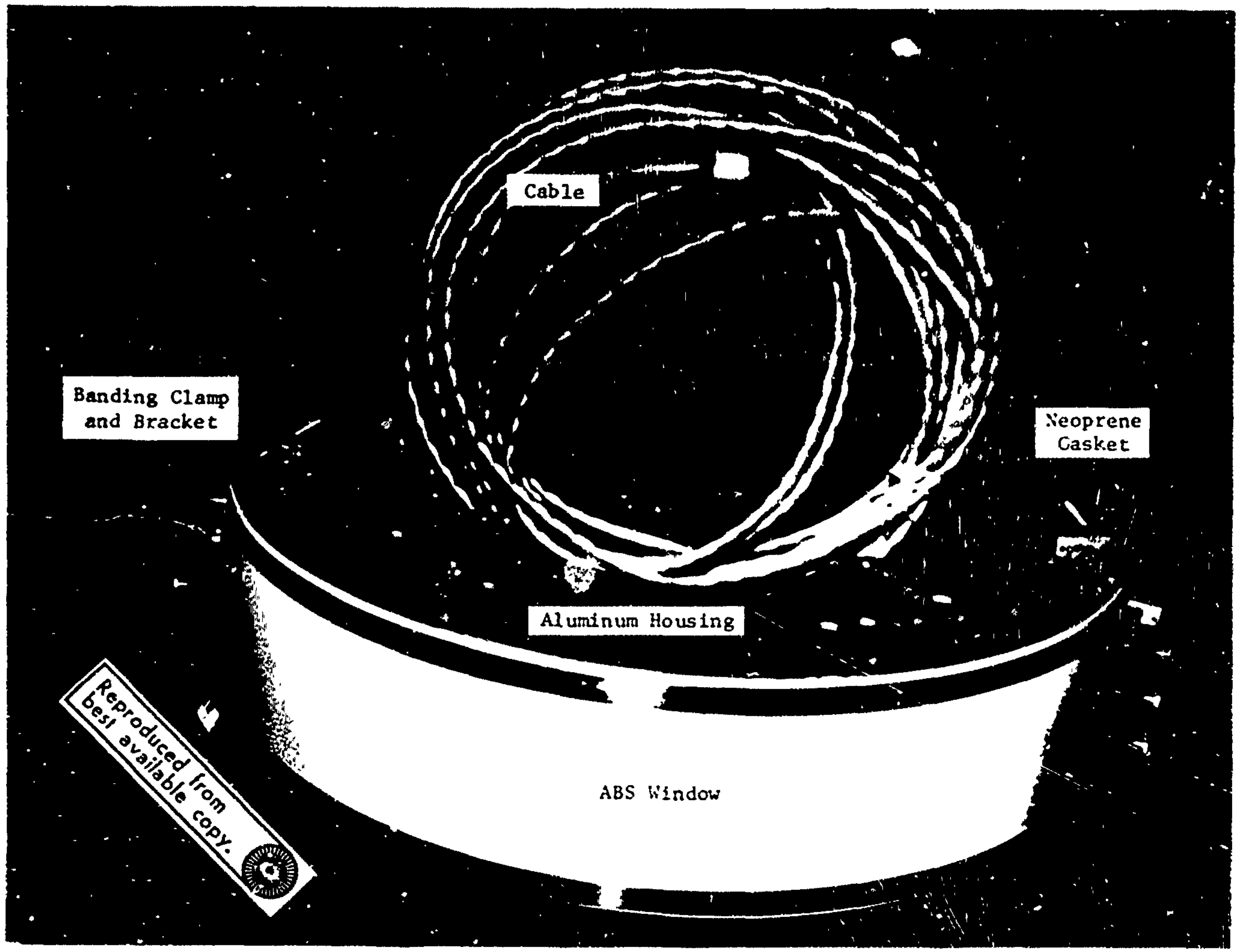

FIGURE 6. TRANSDUCER ARRAY

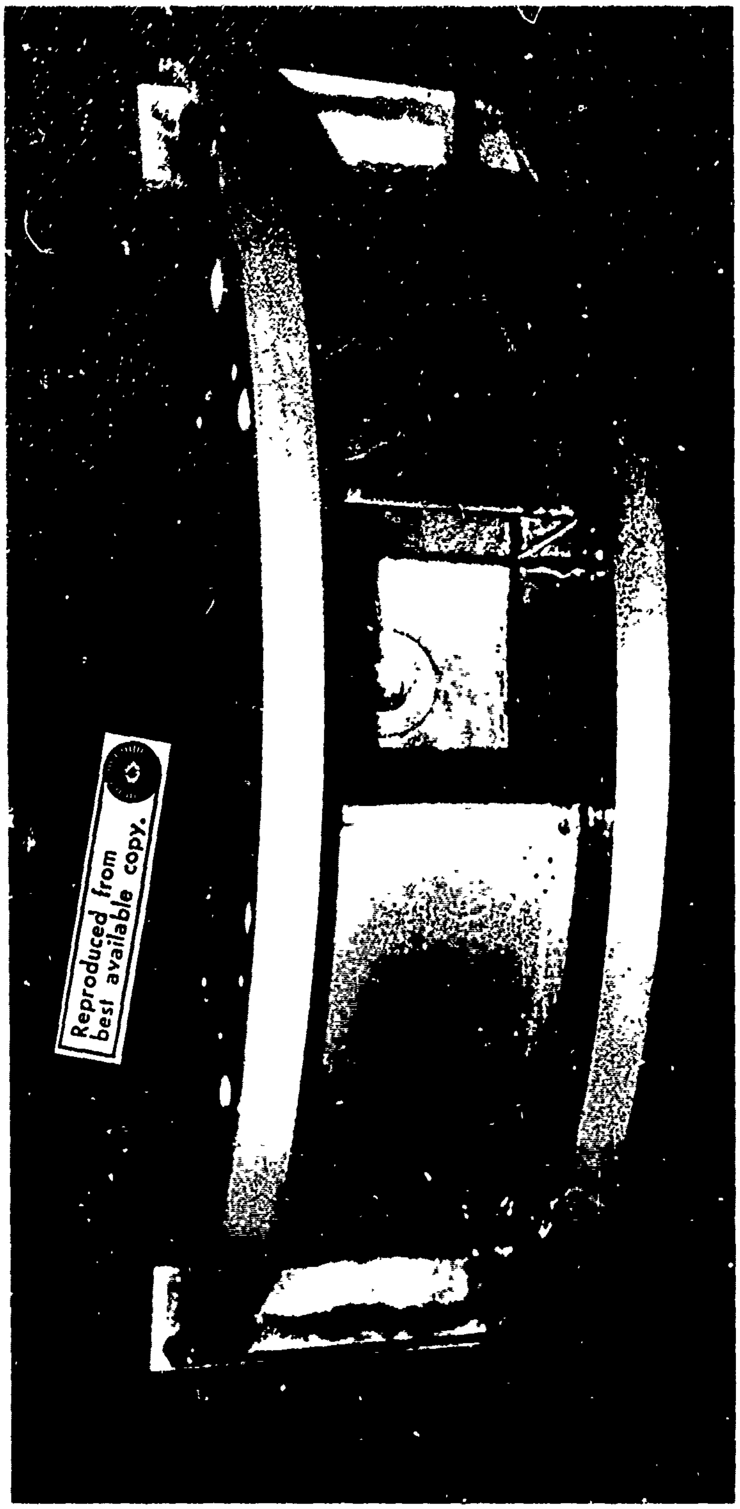
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FIGURE 7. TRANSDUCER HOUSING

WINDOW MATERIAL

The ABS window material shown in Figure 6 is formed from an acrylonitrile-butadiene-styrene material. The electrical and physical properties of this material are described in Reference 5. The acoustic properties of this material were measured at 100 kHz at normal incidence to the materials surface. The measurements showed the material has a reflection coefficient of -16.6 db and a transmission loss of -0.2 db per 1/16 inch thickness. These tests were performed in a small fresh water test tank using NRL Underwater Sound Reference Division E27 hydrophones as sensors.

The nominal thickness of the ABS material is 1/16 inch, and the maximum surface area for mounting elements is 63 square inches.

PIEZOELECTRIC CERAMIC ELEMENTS

The piezoelectric ceramic material used in the transducer is a lead-zirconate lead-titanate composition. This material was commercially developed for sonar applications. The specific ceramic material used in the design was Edo Western's type EC-64. The piezoelectric properties of this material are comparable to Vernitron's PZT-4 and Gulton's HDT-31 as shown in Reference 6. Reference 7 shows Channel Industries 5400 material has similar piezoelectric properties.

As stated in the section on Computation of Array Directivity in YZ-Plane, the dimensions of one sensor element were length 3.1 inches, width 0.172 inch, and thickness 0.535 inch. In the purchase of these elements, it was specified that the elements be polarized in the thickness dimension with silver electrodes fired on the length-width surfaces. Typical elements for the array are shown in Figure 8.

MOUNTING SENSOR ELEMENTS

Figure 9 shows a partial assembly of the transducer array. Some necessary preparatory steps before mounting the sensor elements include:

1. Sanding the glaze off one surface of the ABS window material

2. Indexing the ABS sheet for placement of the sensor elements

3. Attachment of electrodes or hookup wires to the sensor elements

4. Thorough cleaning surface areas to be bonded.

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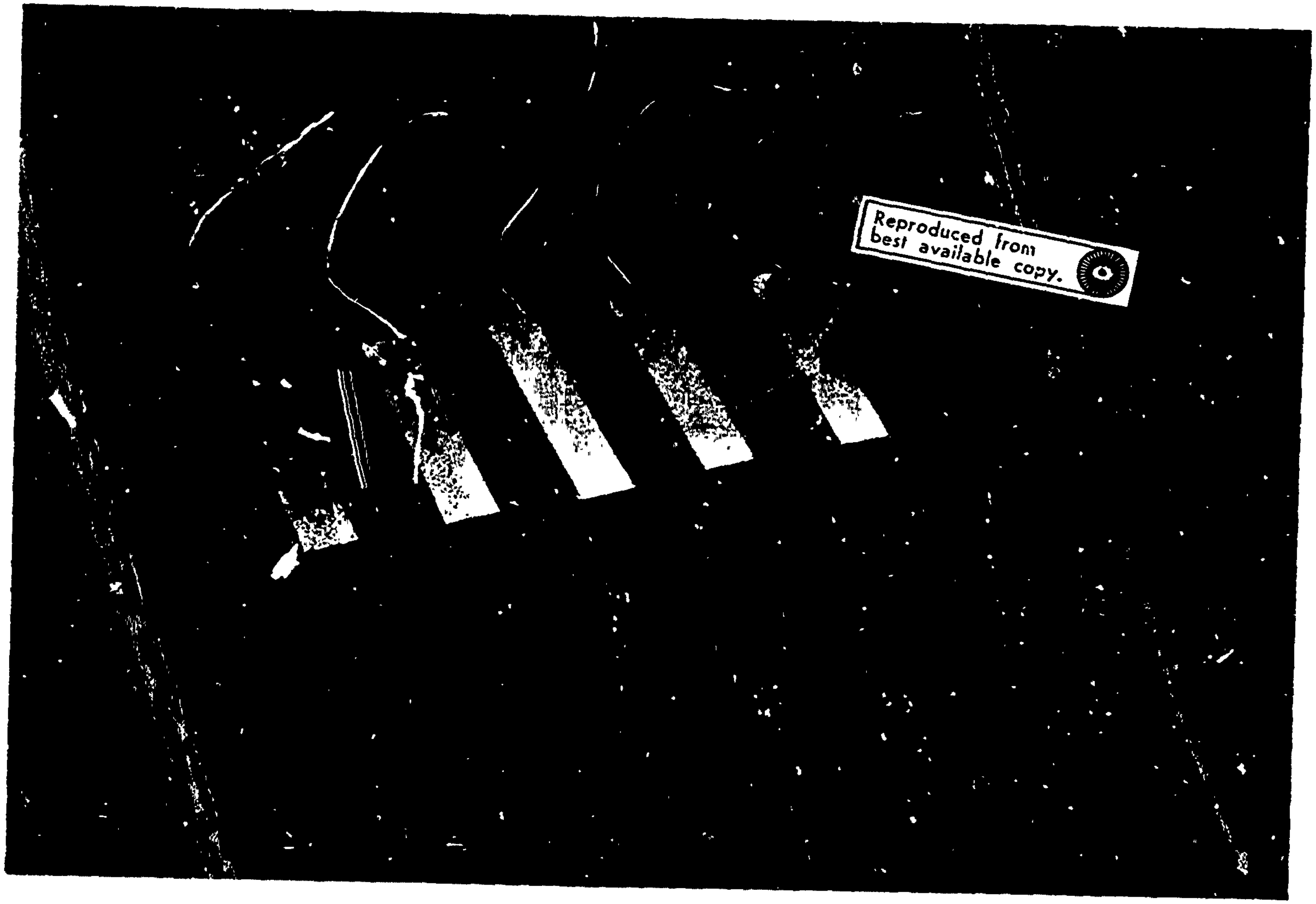
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FIGURE 8. PIEZOELECTRIC CERAMIC ELEMENTS

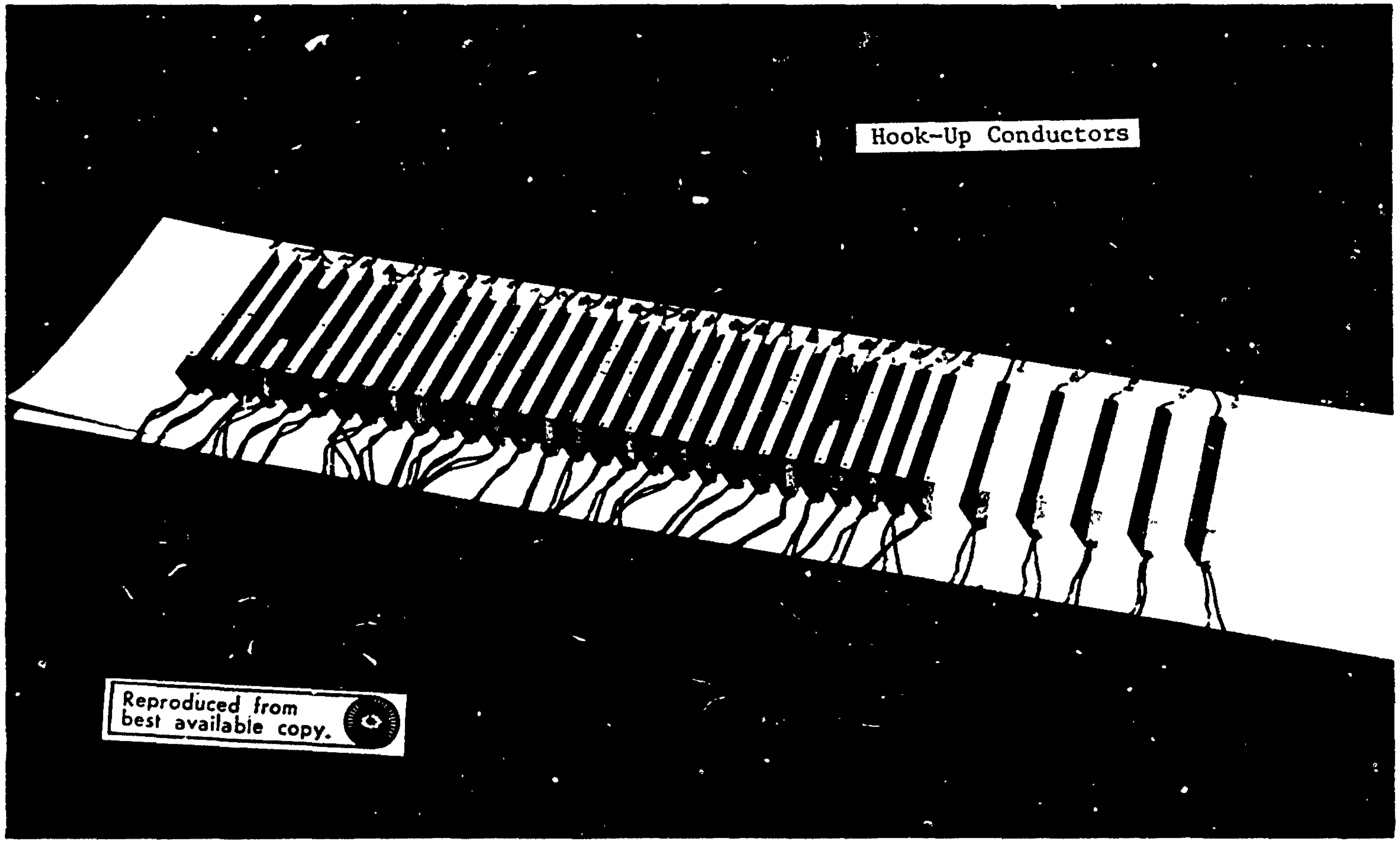

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FIGURE 9. ARRAY PARTIALLY ASSEMBLED

The sensor element can then be bonded to ABS material with a rigid type epoxy. It is suggested that a small weight be placed on the elements during the curing period of the epoxy joint.

In Figure 10 the transducer array is shown fully assembled. The hookup wires have been shortened and interconnected with a flexible insulated conductor. It will be noted at this point that the total surface area of the sensor elements is only 52 percent of the available surface on the ABS window material. This is most important indeed when the designer is attempting to reduce bulk, complexity, and costs.

In Figure 11 the transducer array is flexed to the curvature that closely approximates the curvature of the transducer housing. It can be seen that the elements do not touch when the array is curved.

CABLE

The cable shown in Figure 6 is Belden Type 8718. This is a two-conductor shielded cable with a working voltage rating of 1000 volts. More specific information for the cable can be found in the manufacturer's data sheet.

OPERATIONAL PARAMETERS FOR TRANSDUCER ARRAY

ELECTRICAL PARAMETERS

Some of the electrical parameters for the transducer array are listed in Table 1. The values shown in the table are based on initial design considerations and calculations, i.e., impedance and capacitance.

CAVITATION

In References 3 and 4 the effects of cavitation at the transducer face are discussed. In Reference 4 the attitude was adopted that "cavitation is a statistical affair; the power or voltage limit assigned is a function of the risk on the particular transducer." If a low risk is allowed the intensity at the transducer should be held under 0.3 watt/cm^2. This intensity factor is based on continuous radiation of sound waves on zero submersion (transducer interfaced with water medium) of the transducer array; appropriate increases for depth can be made.

When a transducer array is pulsed at a low duty cycle, the cavitation threshold increases by several orders of magnitude. In Reference 3

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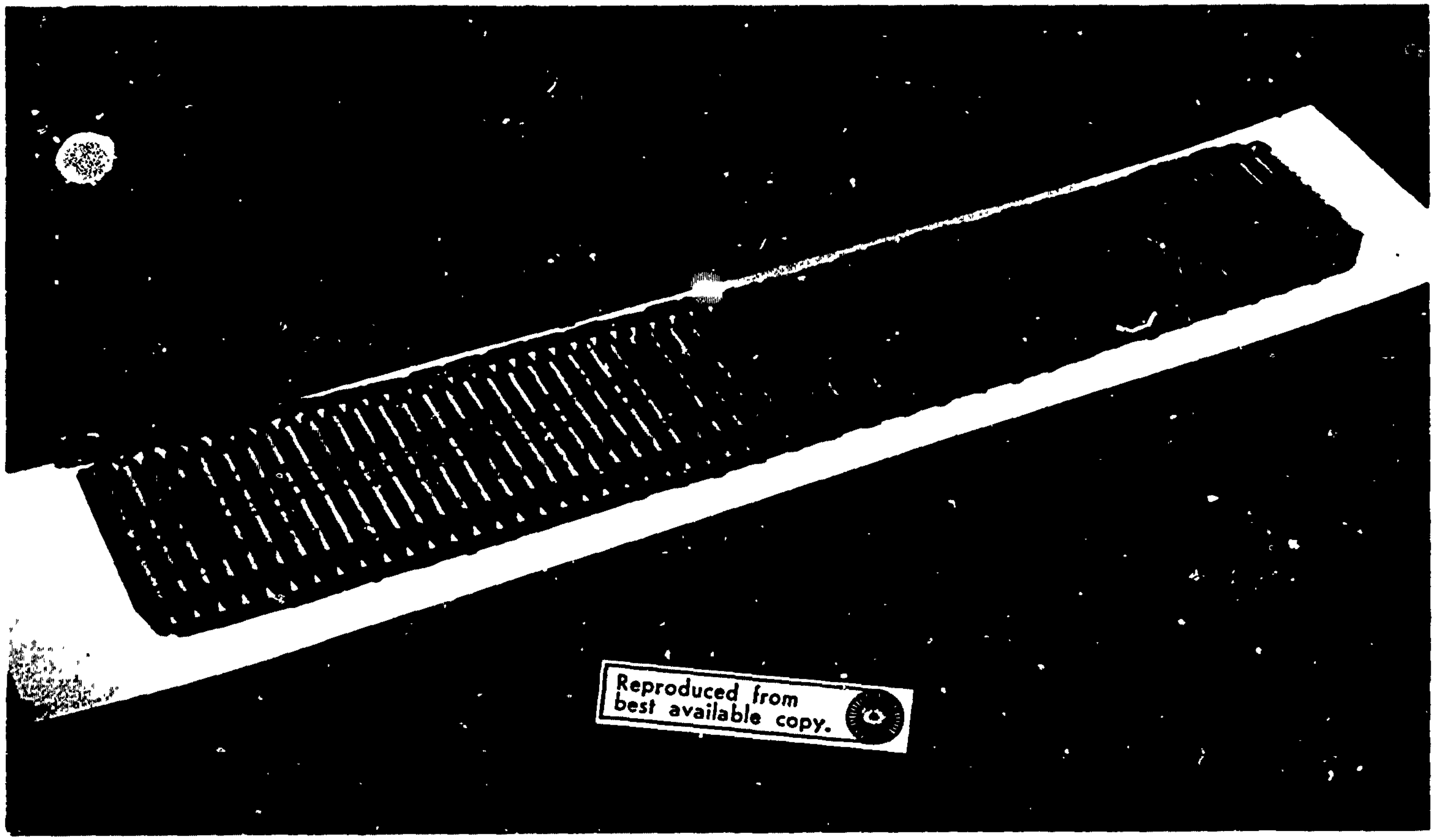
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FIGURE 10. COMPLETED ARRAY

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FIGURE 11. CURVED TRANSDUCER ARRAY

TABLE 1

SUMMARY OF ELECTRICAL PARAMETERS
(INITIAL DESIGN CONSIDERATIONS)

Frequency of Operation	100 kHz
Duty Cycle	0.25 percent
Impedance	21-j 85 ohms
Nominal Capacitance of Array	18,042 pf
Electrical Power Input	4000 Watts
Average Power Dissipated in Transducer Array	10 Watts
Maximum Permissible Input Voltage (Based on 5 Volts/mil to Sensor element)	2600 Volts
Mechanical Quality Factor	31.4

the dependency of cavitation threshold on pulse length is shown for some liquids under different conditions; i.e., gas contant, viscosity, and frequency. Although the data in this reference were not specifically given for a pulse length of 1 millisecond at 100 kHz, a cavitation threshold of 100 watts/cm^2 can be safely extrapolated. Assuming a threshold of 125 watts/cm^2 for the design, the transducer array should therefore be capable of generating an acoustic intensity of 4.15 kilowatts. This approach to analyzing the effects of cavitation for the transducer array seems to be a reasonable prognosis of the situation.

Therefore, from the preceding discussion it appears that the effects of cavitation are not a design constraint, and the field tests, covered in a later section of the report, tends to substantiate this conclusion.

Finally, the present literature on cavitation shows a need for conducting experimental measurements in both fresh and sea water for pulse length of 50 microseconds to 10 milliseconds over the frequency range of 1 kHz to 1000 kHz. This type information would be valuable both to the sonar and transducer designers. The information should be helpful to them when attempting to minimize transducer array costs.

OPERATING DEPTH

The nominal operating depth for the transducer array is 2.3 yards (7 feet). The array can also be operated safely to a depth of 200 feet. The most constraining member in the transducer structure will be the yield strength of the ABS window material; hydrostatic tests should be performed at some future time to establish adequate design criteria.

TESTS AND EVALUATION

ELECTRICAL TESTS

The admittance of the transducer array was measured over the frequency range of 65 to 140 kHz. The data were then converted to an impedance format and the result is presented in Figure 12. The mechanical resonance of the array is 95 kHz for the thickness mode of vibration with an impedance value of 45 ohms. The frequency of maximum impedance (antiresonance) occurs at 113 kHz. At the operating frequency, 100 kHz, the impedance of the transducer array is 72 ohms. The graphical plot of the array impedance is for an untuned electrical condition.

A comparison of the calculated impedance value in Table 1 to the measured impedance in Figure 12 shows a 2:1 difference in values. This difference may be attributed to the effective aperture of the transducer array being greater than originally anticipated. Another contributing factor could be the piezoelectric properties of the ceramic materials being different than stated in the reference literature; properties are usually given for a particular shape and configuration, i.e., a circular disk. Furthermore, the effects of the epoxy joints were not taken into consideration and the impedance of the window material could have been slightly higher than used in the design calculations. It will also be noted that the total calculated capacitance of the array was 18,042 micromicrofarad, whereas upon direct measurement the array capacitance was measured as 15,000 micromicrofarad, a 17 percent difference between the two values.

An equivalent electrical circuit for the transducer array, cable, and a series capacitive reactance is shown in Figure 13. The circuit values were measured with a General Radio 916 AL radio frequency bridge at the operating frequency. The power factor of the electrical network at the cable input was determined to be 0.999; from a practical engineering viewpoint the circuit is resistive.

Considering the circuit values of the transducer array in Figure 13, the reactance shows an inductive value. This is pointed out simply to

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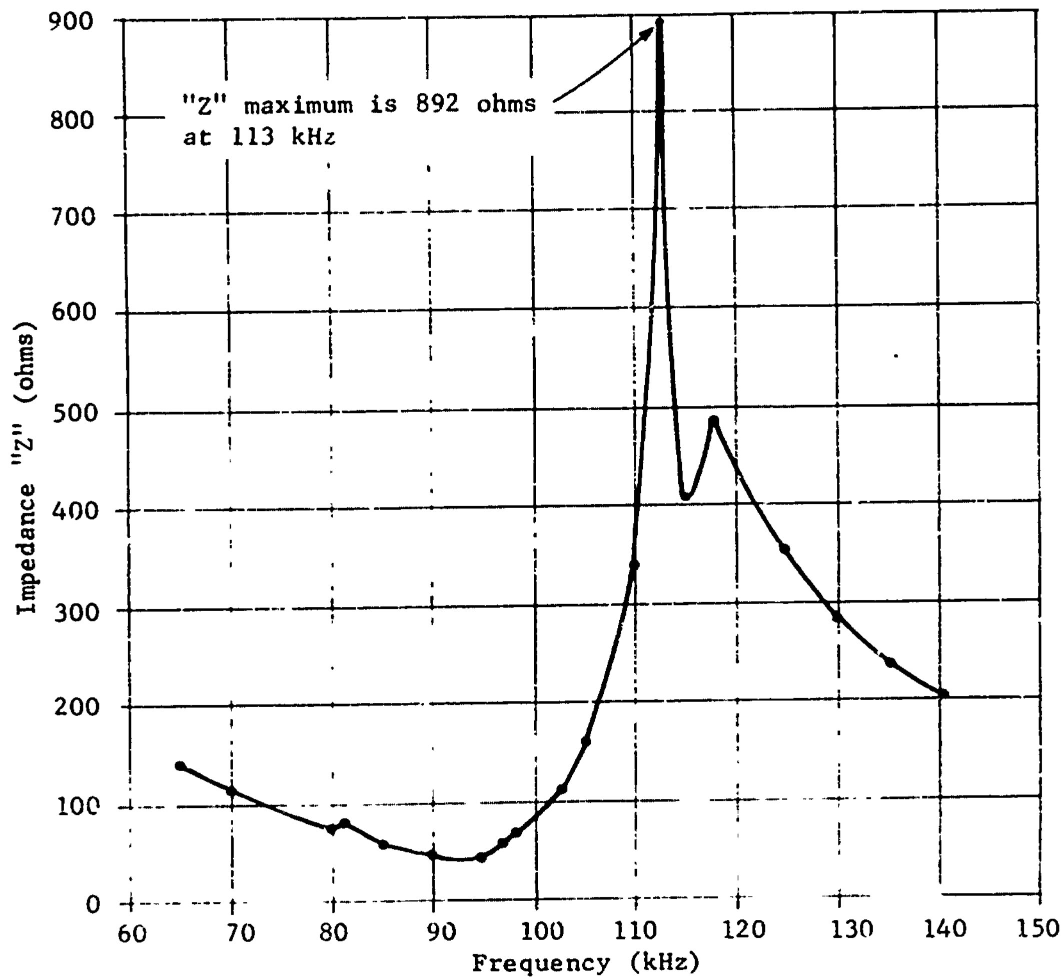

FIGURE 12. IMPEDANCE AS FUNCTION OF FREQUENCY

correlate well-known series electrical circuit theory as discussed in Reference 8. That is, when a series R, L, C circuit is operated above the resonance frequency of the circuit the reactance portion of the impedance will appear inductive. Thus, at the operating frequency the transducer array is being operated slightly above fundamental thickness resonance and its reactance is indeed inductive.

One additional point should be made in regard to the equivalent circuit of Figure 13, and this relates to the transmission line or cable. The cable presents an additional series impedance ($Z = R + jX$) in the electrical circuit, and when one attempts to analyze or electrically tune the transducer array over a cable, appropriate consideration must be given to the cable impedance. This is a tedious and laborious task when the GR-916AL Bridge is used, and measurement errors can easily be introduced. Finally, the 1580-ohm resistor shunted across the cable was used to dampen the acoustic response of the transducer array, and its value was determined experimentally.

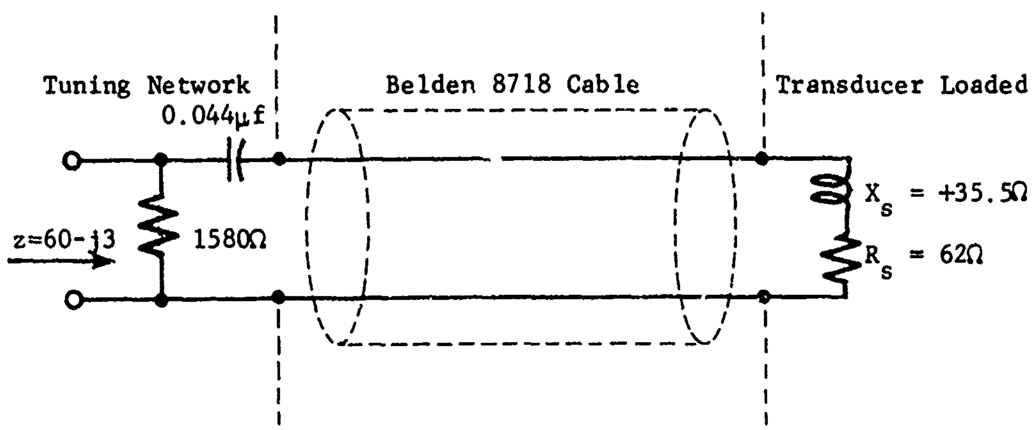

FIGURE 13. EQUIVALENT ELECTRICAL CIRCUIT OF TRANSDUCER ARRAY CABLE, AND TUNING NETWORK AT 100 kHz

ACOUSTICAL TESTS

Transmitting Response

The transmitting response for the transducer array for a series tuned condition is shown in Figure 14. The acoustic peak for the array is 163.6 db ref 1 μPa at 1 yard per volt at 100 kHz. The effective quality factor is 8.25.

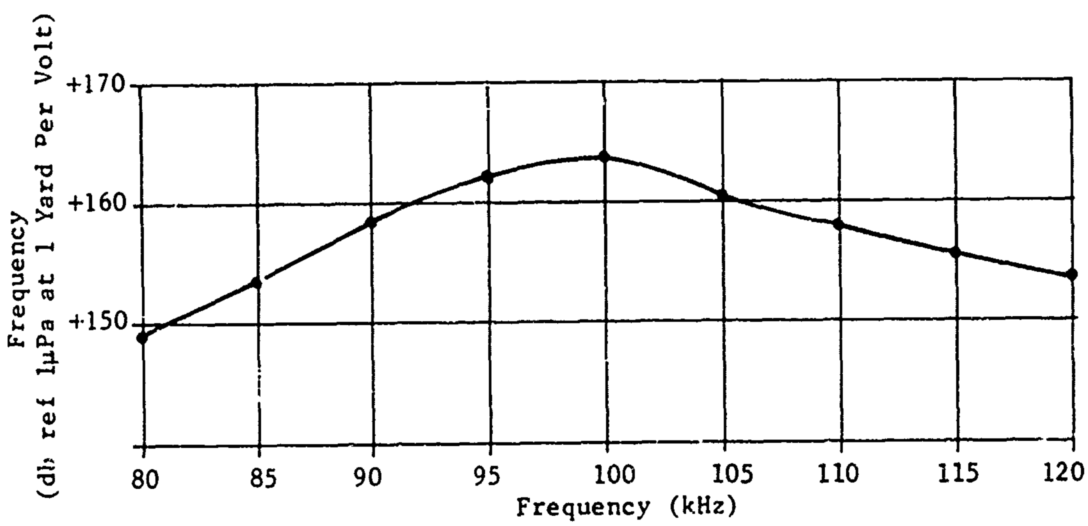

FIGURE 14. TRANSMITTING RESPONSE AS A FUNCTION OF FREQUENCY

In Figure 14 the feasibility of electrically tuning a transducer array above its mechanical resonance and achieving a satisfactory power output from the array is demonstrated. Conversely, the transducer array could be tuned below the mechanical resonance and achieve similar results. This will be quite important when the designer is attempting to minimize the cost for the transducer array.

Directivity in XY-Plane

In Figure 15 a measured directivity pattern is compared to one of the theoretical predicted patterns previously shown in Figure 5. For convenience the array parameters are restated in the figure legend. The difference in radius-of-curvature and number of elements is of no consequence as shown in Figure 4. However, the center-to-center spacing and slot width between elements was found to be of paramount importance. Thus, Figure 15 shows excellent agreement between the theoretical and experimental directivity patterns.

FIELD TESTS

The transducer array was frequently tested in St. Andrew Bay close to the laboratory during the period 15 May through 12 August 1971. The array was electrically driven with a switching power amplifier at various power levels up to 3.1 kilowatts. Usually these power levels were applied for time intervals of 2 to 3 hours. When the array was not in use it was removed from the bay and stored in a position so that the array aperture was exposed to sunlight.

In September 1971 the impedance of the transducer array was measured to determine if any significant changes in impedance had occurred during the field tests. The measurement showed the array impedance to be $Z = 60 - j10$. The reactance component was found to be slightly higher (refer to Figure 13) and was probably due to the aging factor of the piezoelectric sensor element, and to a lesser extent on a change in the elasticity of the epoxy joints; in any event, the power factor of the electrical circuit remains high (0.988) and the transducer array will be used in further field tests.

Also, during these initial field tests, it was found that the transducer array did not exhibit any of the usual symptoms associated with cavitation, nor did the transducer array show any signs of overheating.

CONCLUSIONS

Based on the development efforts described in the report, the following major conclusions are drawn:

1. A simple procedure for fabricating a transducer array with sparsely-spaced sensor elements (an array packing factor of 52 percent)

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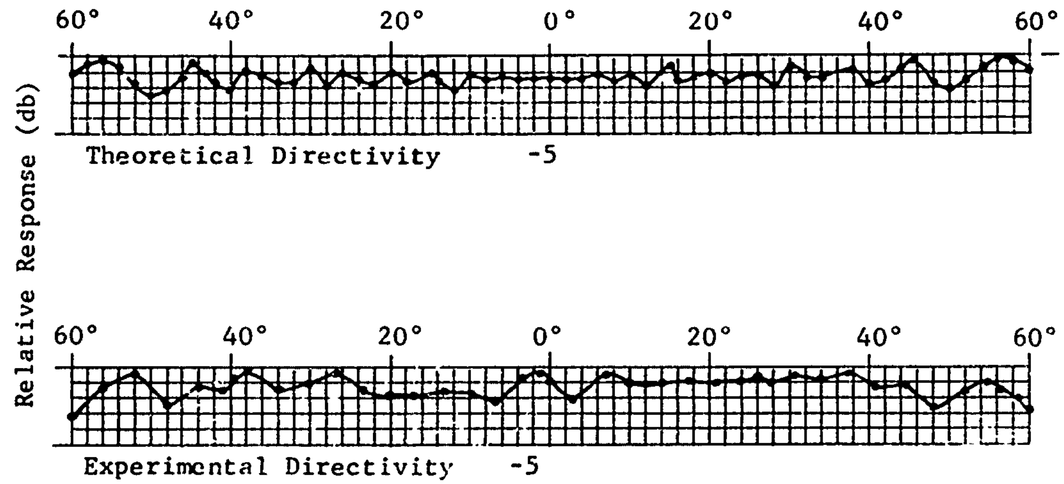

Radius of Curvature	Number of Elements in Array
9"	58
9.5"	62

FIGURE 15. A COMPARISON OF THEORETICAL AND EXPERIMENTAL DIRECTIVITY PATTERNS IN XY-PLANE

that will exhibit wide-angle sonic transmission characteristics has been successfully demonstrated both theoretically and experimentally. This effort lends itself to lowering costs for wide-angle transducer arrays.

2. Electrical tests (impedance) have shown that long thin ceramic bars can be used in the curved-faced transducer array, and the need for element dicing is unnecessary.

3. The feasibility of electrically tuning a transducer array whose impedance contains an inductive reactance component has been demonstrated.

4. The transducer array in field tests has been driven with an input power level of 3.1 kW, or with an input voltage of 900 volts peak-to-peak. The effects of cavitation or element overheating were not observed.

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